REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
30-09-2011	Final	15/04/08-30/06/11

4. TITLE AND SUBTITLE
MULTI-SCALE PREDICTION AND SIMULATION OF LOCALIZATION BANDING IN GRANULAR MEDIA

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-08-1-0192

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Jose E. Andrade

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Northwestern University

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
875 North Randolph Street
Suite 325, Rm 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-OSR-VA-TR-2012-0254

12. DISTRIBUTION/AVAILABILITY STATEMENT
A

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Shear bands are a critical factor in the response of granular materials, such as soils, rocks, and concrete. The objective of this research is to develop methods for accurately predicting the onset and propagation of deformation bands in granular media under extreme environments by developing an efficient multiscale simulation framework. The goal is to bridge continuum scale methods with the existing discrete methods to obtain an accurate multiscale model that can be used to predict and model shear band inception and propagation in granular media. Fundamental understanding of granular mechanics under shear banding will pave the way to tackling more challenging phenomena such as projectile penetration and blasting.

15. SUBJECT TERMS
Penetration, granular matter, multiscale modeling, numerical methods

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU		

Reset

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18
Adobe Professional 7.0

MULTISCALE PREDICTION AND SIMULATION OF LOCALIZATION BANDING IN GRANULAR MEDIA

FA9550-08-1-0192

José E. Andrade
Division of Engineering and Applied Science
California Institute of Technology, CA

Ted Belytschko
Department of Mechanical Engineering
Northwestern University, Evanston, IL

Abstract
Shear bands are a critical factor in the response of granular materials, such as soils, rocks, and concrete. The objective of this research is to develop methods for accurately predicting the onset and propagation of deformation bands in granular media under extreme environments by developing an efficient multiscale simulation framework. The goal is to bridge continuum scale methods with the existing discrete methods to obtain an accurate multiscale model that can be used to predict and model shear band inception and propagation in granular media. Fundamental understanding of granular mechanics under shear banding will pave the way to tackling more challenging phenomena such as projectile penetration and blasting.

Status/Progress
A key component for the success of the multiscale scheme is the ability to extract the continuum behavior directly from the granular scale. To achieve this goal, a number of objectives have been successfully achieved: 1. The design and implementation of a semi-concurrent multiscale scheme to extract material behavior from the granular scale and pass it onto the continuum scale [1], 2. The creation of a novel semi-implicit return mapping algorithm to enable the semi-concurrent multiscale computations [2], 3. Development of constitutive models capable of capturing rate effects [3], 4. Design and implementation of parallel algorithms to perform multi-unit cell calculations [4, 6]. In addition to these achievements, final efforts focused on crucial aspects dealing with the development of a new hierarchical multiscale method amenable to direct linkage with experimental and numerical granular kinematics [6], and the development of multiscale failure modeling methods linking assumed enhanced strain (AES) finite elements [5] with discrete element calculations. In this final report for this project, we focus on the overall achievements.

Perhaps the two most important achievements in this project were: 1) development of the first predictive (validated) multiscale method for failure modeling in granular materials and 2) multiscale enhancement of existing failure modeling techniques such as Assumed Enhanced Strains (AES) to accurately model multiscale failure in granular solids. These achievements enabled us to accomplish the goals proposed for this project, which are shown pictorially in Figure 1.

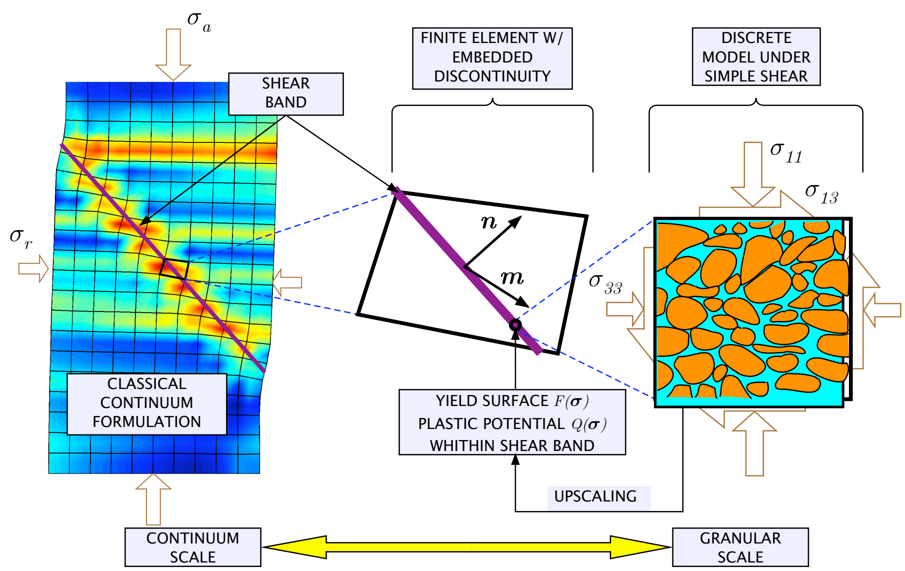

Figure 1. Schematic of proposed research and its main goal: to enhance elements with embedded discontinuities within a multiscale framework connecting continuum and granular scales.

To showcase the aforementioned achievements, we will focus on the last publication conceived during this project [5]. In this paper, we developed a new Assumed Enhanced Strain (AES) technique, using an original formulation proposed in [7]. The original formulation enriched elements but could not describe plasticity inside shear bands accurately. Our new method accesses the granular scale to enhance the constitutive description at the AES continuum level. Figure 2 shows an example of simulations performed using discrete mechanics and compared with simulations using the AES multiscale technique.

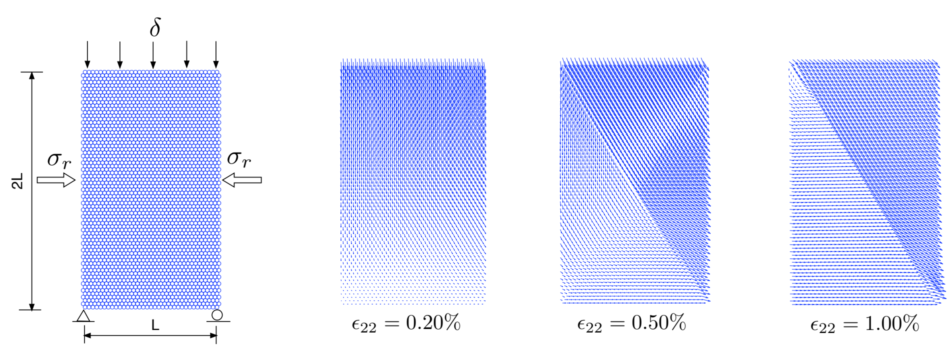

Figure 2. Sample (left) composed of regularly packed granular materials under plane strain compression. A shear band develops when vertical strain is about 0.5%, with this shear band dominating the process for the duration of the discrete element simulation.

We used our proposed AES technique to simulate the aforementioned sample of granular material under the same boundary conditions. Figure 3 shows the results using a triangular irregular mesh enhanced with AES elements that have multiscale capabilities to describe the constitutive response based on the grain scale mechanics. This figure also shows a comparison between the global stress-strain responses between the multiscale AES and the direct numerical simulation using discrete mechanics (DEM). Clearly, the method is able to capture the most salient features related to overall strength of the sample and the topology of the shear band.

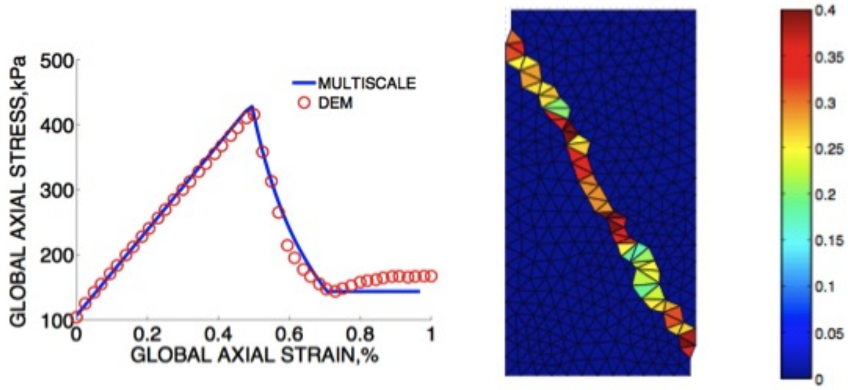

Figure 3. Results comparing multiscale AES with direct simulations using discrete mechanics (DEM).

Finally, we have shown that the method can be validated using actual experiments. This is the first method of its kind to be ever compared with actual physical experiments. In reference [5], we compare the multiscale AES method with physical experiments on sands where a dominant shear band was observed. Micromechanical information measured during the test was used to construct the hierarchical multiscale AES calculation. Figure 4 shows the results of the multiscale AES prediction compared with experimental data. It can be seen that the method clearly captures the macroscopic response of the sample accurately.

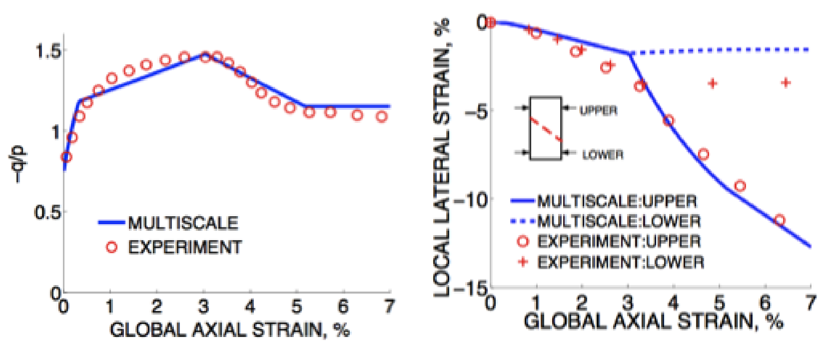

Figure 4. Comparisons of multiscale AES with physical experiments where a dominant shear band was observed.

Acknowledgment/Disclaimer
This work was sponsored (in part) by the Air Force Office of Scientific Research, USAF, under grant/contract number FA9550-08-1-1092. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the Air Force Office of Scientific Research or the U.S. Government.

References

1. J. E. Andrade and X. Tu. Multiscale framework for behavior prediction in granular media. *Mechanics of Materials*, 41:652-669, 2009.

2. X. Tu, J. E. Andrade, and Q. Chen. Return mapping for nonsmooth and multiscale elastoplasticity. *Computer Methods in Applied Mechanics and Engineering*, 198:2286-2296, 2009.

3. J. E. Andrade and X. Tu. Multiscale modeling of granular media. In H.I. Ling, A. Smith and R. Betti, editors, *Poromechanics IV*, Columbia University, New York, 2009.

4. J. E. Andrade, X. Tu and C. F. Avila. Multiscale modeling of granular matter: connecting the continuum and granular scales. In E. Onate and D.R.J. Owen, editors, *COMPLAS X*, Barcelona, Spain, September 2009. In CD-ROM.

5. Q. Chen, J. E. Andrade, and E. Samaniego. AES for multiscale localization modeling in granular media. *Computer Methods in Applied Mechanics and Engineering*, In press, 2011.

6. J. E. Andrade, C. F. Avila, S. A. Hall, N. Lenoir, G. Viggiani. Multiscale modeling and characterization of granular matter: from grain kinematics to continuum mechanics. *Journal of the Mechanics and Physics of Solids*, 59:237-250, 2011.

7. R. I. Borja. A finite element model for strain localization analysis of strongly discontinuous fields based on standard Galerkin approximations. *Computer Methods in Applied Mechanics and Engineering*, 190:1529-1549, 2000.

Personnel Supported During Duration of Grant

J. E. Andrade	Associate Professor, Caltech, Pasadena, CA
T. Belytschko	Professor, Northwestern University, Evanston, IL
X. Tu	Post-Doctoral Fellow, Northwestern University, Evanston, IL
C. F. Avila	Post-Doctoral Fellow, Caltech, Pasadena, CA
Q. Chen	Ph.D. Candidate, Northwestern University, Evanston, IL

Publications

- J. E. Andrade. Predictive framework for multiscale computations in granular media. In B. A. Schrefler and U. Perego, editors, *WCCM8 and ECCOMAS 2008*, Venice, Italy, in CD ROM (2008).
- J. E. Andrade. Predicting behavior in granular materials via multiscale computations. Proceedings for the *XXII International Congress in Theoretical and Applied Mechanics*, Adelaide, Australia, in CD-ROM, 2008.
- X. Tu and J. E. Andrade. Multiscale modeling of indenter penetration in granular media. In *Society of Engineering Science Forty-Fifth Annual Technical Meeting*, Urbana-Champaign, IL, 2008.
- X. Tu, Q. Chen and J.E. Andrade. A new strategy for implementing plasticity models for cohesive-frictional materials. In Proceedings for the *Inaugural International Conference of the Engineering Mechanics Institute*, Minnesota, MN, 2008.
- J. E. Andrade. Modeling geomaterials across scales (keynote). In *European Geophysical Union Congress*, Vienna, Austria, April, 2009.
- J. E. Andrade and X. Tu. Multiscale modeling of granular media. In H.I. Ling, A. Smith and R. Betti, editors, *Poromechanics IV*, Columbia University, New York, 2009.
- J. E. Andrade and X. Tu. Multiscale framework for behavior prediction in granular media. *Mechanics of Materials*, 41:652-669, 2009.
- X. Tu, J. E. Andrade, and Q. Chen. Return mapping for nonsmooth and multiscale elastoplasticity. *Computer Methods in Applied Mechanics and Engineering*, 198:2286-2296, 2009.
- J. E. Andrade, X. Tu and C. F. Avila. Multiscale modeling of granular matter: connecting the continuum and granular scales. In E. Onate and D.R.J. Owen, editors, *COMPLAS X*, Barcelona, Spain, September 2009. In CD-ROM.
- J. E. Andrade and C. F. Avila. Predictive multiscale modeling of granular matter: from discrete mechanics to continuum mechanics. In the *10th US National Congress on Computational Mechanics*, Columbus, Ohio, July, 2009.
- J. E. Andrade, C. F. Avila. Capturing strain localization in granular matter with multiscale computations. In the *World Congress on Computational Mechanics*, Sidney, Australia, July, 2010.
- Q. Chen and J.E. Andrade. Modeling post-localization behavior in granular materials using a multiscale strong discontinuity approach. In Proceedings for the *16th US National Congress of Theoretical and Applied Mechanics*, State College, Pennsylvania, 2010.
- J. E. Andrade, C. F. Avila. Multiscale computations for the prediction of shear bands in granular materials. In the *16th US National Congress of Theoretical and Applied Mechanics*, Pennsylvania, July, 2010.
- J. E. Andrade, C. F. Avila. Experiment based multiscale computations in granular materials. In *Geo-Frontiers: Advances in Geotechnical Engineering*, Dallas, March, 2011.

- J. E. Andrade, C. F. Avila, C. Mihalache. The lifecycle of avalanches: Modelling and simulations. In the *11th US National Congress on Computational Mechanics*, Minnesota, July, 2011.
- J. E. Andrade, C. F. Avila, S. A. Hall, N. Lenoir, and G. Viggiani. Multiscale modeling and characterization of granular matter: from grain kinematics to continuum mechanics. *Journal of the Mechanics and Physics of Solids*, 59:237-250, 2011.
- Q. Chen, J. E. Andrade, and E. Samaniego. AES for multiscale localization modeling in granular media. *Computer Methods in Applied Mechanics and Engineering*, In press, 2011.

Honors & Awards Received

- ASCE's Arthur Casagrande Professional Development Award, 2011
- AFOSR Young Investigator (YIP) Award, 2010
- NSF CAREER Award, CMMI Division, 2010
- Natural National Science Foundation Young Researcher Fellowship, China, 2009
- U.S. National Academy of Engineering Frontiers of Engineering Symposium, participant, Albuquerque, NM (2008)
- USNC/TAM Fellowship, International Congress in Theoretical & Applied Mechanics, Adelaide, Australia (2008)
- USACM Fellowship, 8th World Congress in Computational Mechanics, Venice, Italy (2008)

AFRL Point of Contact

William L. Cooper, PhD
Air Force Research Laboratory
AFRL/RWMW

Transitions
None.

New Discoveries
Discovered efficient and accurate numerical algorithms for multiscale analysis of failure in granular solids. Discovered a set of parameters that are key in capturing the behavior of granular materials under plastic deformation. These discoveries are relevant and easily transferable to other solid materials where multiscale deformation and failure takes place.